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A Review on Different Models for Heat Transfer Assessment in Hydrocarbons Fires

Yashwant Buke[*1], **Sanjay Jain**[2], **Praveen Patel**[3]
[*1,2,3] Department of Fire Technology & Safety Engineering, IES IPS Academy, Indore Madhya Pradesh, India
yashbuke08@gmail.com

Abstract

Since the beginning of industrial revolution, accidents caused by the hydrocarbons are increased significantly. In order to reduce the accidents and unintentional events, this project considers heat transfer assessment of fires of safety pertaining to bulk storage of liquids and gases in a petroleum refinery.

According to the classification of various types of storage tanks for liquid and gas are taken into account and it also suggest the design and construction criteria for the safe storage. It deals over various problem and difficulties of oil and gas industries like BLEVE, UVCE, Fire Ball Hazard, LPG Hazard and many more.

When proper attention towards heat transfer assessment of fires in bulk storage of hydrocarbons, separation distances of storage tanks, secondary containment, application of water and foam against fire protection, fire alert systems etc are in action, there will be sound result in terms of safety of health, environment and property.

Keywords: Heat Transfer, Hydrocarbons Fires

Introduction

Heat transfer is energy in transit due to temperature difference. Whenever there exist a temperature difference in a medium or between media, heat transfer must occur. The basic requirement for heat transfer is the presence of temperature difference. There can be no net heat transfer between two mediums that are at the same temperature. The temperature difference is the driving force for heat transfer, just as the voltage difference is the driving force for electric current flow and pressure difference is the driving force for fluid flow. The rate of heat transfer in a certain direction depends on the magnitude of the temperature gradient (the temperature difference per unit length or the rate of change of temperature) in that direction. The larger the temperature gradient, the higher the rate of heat transfer.

Heat transfer is major problem in the industrial sector; it may results in the fire. Hydrocarbons, especially fuels (gasoline, diesel, LPG etc.) are stored in above – ground tanks or spheres. The total energy thus stored at any one tank farm is enormous indeed. As one tank catches fire, the nearby tanks are cooled by water sprays to prevent them from burning. Huge quantity of water is used. This water has to be treated before being discharged or reused. To optimize the cost of fire fighting we are looking at all aspects of heat transfer from a burning tank to a nearby tank, heat transfer within the 2nd tank and heat removal from it by water spray. Boundary layer flow and its detachment from the surface also come in. The work may eventually lead to modifications in tank design, water spray system, inter - tank spacing**.**

Gas Fires

When a flammable gas is released into the atmosphere, different kinds of fires may occur dependent on the release mode and the degree of delayed ignition. Thus, it is convenient to divide gas fires into the following types:

- Flash Fire or Cloud Fire
- Jet Fire or Flare Fire
- Diffusive Gas Fire

'Flash Fires' or 'Cloud Fires' result from a delayed ignition of a release of gas or vapour forming a cloud which disperses downwind. There is a low probability for detonation of the cloud provided that no flame accelerating obstacles or confinements are present in the location of the cloud. However, flash back or burn back may occur. That is, the flame consumes the premixed portion of the cloud and propagates back toward the fuel source without creating any pressure or blast effects. Thus, a flash fire is a highly transient fire which has a very short duration usually less than 1 minute. The main hazard from a flash fire is thermal radiation to human beings.

A 'Jet Fire' results from a high pressure leakage of a flammable gas. Because of the high exit velocities of the gas, jet fires are often termed as 'momentum controlled' fires due to the fact that the momentum force prevails over the buoyancy force in large parts of the flame plume. However, at some distance from the exit, the gas velocity is reduced to a level at which the buoyancy force is dominant. The fire is from that point more like a buoyancy controlled jet fire. The term 'Jet Fire' is also often used in case of less momentum controlled fires. However, the term 'Flare Fire' is more convenient for these kinds of fires. The terms 'Jet Fire' and 'Flare Fire' are often used interchangeably.

A 'Diffusive gas fire' is a fire which results from a diffusive release of a flammable gas through a comparatively large opening. A diffusive gas fire will emerge from the opening if the gas is being ignited. In contrast with jet fires, a diffusive gas fire is a 'buoyancy controlled' fire because of the diffusive release of gas. The buoyant force is the dominant force in the entire flame plume.

Heat transfer assessment of flash fire

A flash fire may occur if there is a release of a flammable gas or vapour in the open forming a gas cloud followed by a delayed ignition of the gas cloud. The gas or vapour release can either be continuous or more or less instantaneous. The first case may result from a continuous gas release or a liquid release from which there is a considerable amount of gas or vapour flashing from a not ignited liquid pool. A failure of a vessel containing LNG or LPG may cause this situation. There will be a considerably flash evaporation from the liquid pool around the vessel. Thus, a continuous vapour cloud is formed downwind from the fuel source (see Figure1).

Due to the fact that in recent years there has been an increasing tendency to transport and store liquefied gaseous fuels (e.g. LNG and LPG) in large vessels, the term flash fires became synonymous with the term 'Vapour Cloud Fires' in spite of the fact that this fire scenario may also result from a pure gas release.

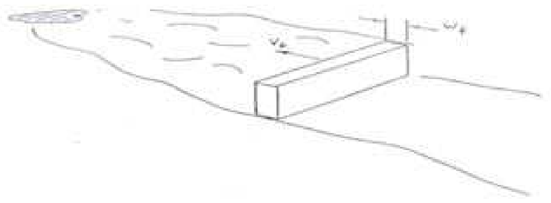

FIGURE 1: Model for vapour cloud burning (where V_f is the flame velocity and W_f is the width of the flame front.

If wind is present, the gas cloud disperses downwind and entrains air which mixes with the gas. Sooner or later the gas cloud may encounter an ignition source.

A presupposition for ignition of the cloud is that the concentration within the cloud must be within the flammability limit range of the released substance.
Another requirement which has to be met in order to achieve a flash fire is that at the location of ignition source there cannot be any obstacles or confinement causing an acceleration of the flame front. This may result in an explosion with comparatively large pressure effects rather than a flash fire. A characteristic feature of flash fires is that they do not cause any blast effects. The flame travels backwards to the fuel source through the premixed regions of the cloud.

Since a flash fire has a very short effective fire duration (i.e. in the order of few seconds), it is not necessary to consider the heat transfer to structures. Further, due to the fact that flash fires usually are elevated from the ground, personnel will only receive incident radiative heat flux. It has been customary to assume that personnel directly exposed to the flash fire will be killed immediately. Thus, only radiative heat transfer to external targets will be considered.

Due to the very short duration and the highly transient characteristics of flash fires, the average incident heat flux received by an observer is a complex function of many factors. For example, it is hard to estimate an appropriate surface emissive power and in what time interval this emissive power is valid.
The net effective thermal radiation heat flux, q"r (kW/m^2), to a target at some distance from the flash fire is given by:

$$q_{r\ net}'' = \sigma F(T_g^4 - T_a^4) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

Where,
F = is the view factor between the flash fire and the target (For close target, the view factor can be set equal to unity.
T_g = effective radiation temperature of the flash fire (K)
$T_{a\,=}$ ambient temperature (K)
σ = Stefan Boltzmann's constant = $56.7\text{x}10^{-12}$ $kW/m^2.K^4$

Assessment

A total mass of 10000 kg of LNG is released into atmosphere. The vapour cloud of LNG is formed. The cloud encounters an ignition source approximately 100 m from the release point. The net effective thermal radiation heat flux is predicted on the ground just below the flash fire when the adiabatic flame temperature is 1950^0c and ambient temperature is 10^0c.

In this case the flash fire is rather close to the target and the view factor can be taken equal to unity. The net effective thermal radiation heat flux, q_r'' (kW/m^2) will be according to Eqn.(i)

$$q_{r\,net}'' = 1384\ kW/m^2 \qquad \ldots\ldots\ldots\ldots\text{(2)}$$

Heat transfer assessment of Jet fire

A Jet fire may result from a high pressure leakage of gas from process plants or storage tanks. An accidental leakage of gas may occur from flanges or ruptures in pipes. Storage tanks or process vessels containing for example liquefied petroleum gas (LPG) which is exposed to an enveloping fire, will after a very short period of time vent their contents through a relief valve. If the released gas is ignited, a jet fire of length 5 - 50 m can be the result. Even worse is the case of a gas blowout above drill floor on an offshore production platform creating a free jet. Gas discharge rates even above 100 kg/s may be burned almost completely in the jet fire.

Jet fires are characterized by a high momentum jet flame which is highly turbulent. The flame is lifted above the exit opening from which the gas is discharged generally at very high pressures. This distance, which is often termed as 'lift-off' or 'blow-off' appears because the combustion process can only take place when the flow velocity is reduced sufficiently to allow stable combustion.

Another feature of such fires is the high entrainment of air into the flame plume due to highly turbulent flame. An air entrainment from 4-5 times of that required for stoichiometric combustion is reported. Due to the efficient mixing of fuel and air, such flames may exhibit higher flame temperatures than ordinary buoyancy controlled diffusion flames. Thus, such fires may create extremely high heat radiation zones in the vicinity of the fire.

Due to the extremely high flow velocities, the convective heat transfer to objects engulfed by the fire may even exceed the radiative heat transfer in large scale turbulent jet fires in the early phase of fire exposure.

The jet fires scenarios previously described are a result of an accidental release of gas. Similar fires may also occur in case of intentional disposal of unwanted gas in flares. Flaring is the combustion process that has been the traditional method for disposal of large quantities of unwanted gases and vapour in both the offshore industry and the petroleum industry on land.

'Production flaring' is a method for safe disposal of unwanted gas in the oil industry, while 'Process flaring' is a method for disposal of gas which has passed through safety valves protecting various process equipments or tanks. The case initially described in which large amounts of gas have to be disposed of safely in case of an emergency situation such as fire, power failure, or overpressure in a process vessel, is termed as 'Emergency flaring'.

Fires which are a result of flaring, are often termed as a 'Flare fires' rather than 'Jet fires'. However, there is no sharp distinction between these two terms and they are often used interchangeably. In flaring the gas is released through nozzles which may cause supersonic exit velocities of the gas. It is impossible to achieve supersonic exit velocities in cases of accidental gas releases in which the gas is discharged from ruptured pipes, flanges or through holes in a process vessel. The maximum exit velocity in this case will be the sonic velocity (the velocity of sound of the gas at the gas *exit* conditions). The *exit* velocity is sonic if the upstream pressure (i.e. pressure of fuel source) is higher than 1.7 - 1.9 bar for most gases!). Consequently, a sonic exit velocity is achieved in most actual leak situations from process plants and storage tanks.

There are two types of methods used for the heat transfer assessment of jet fire:

(i) The point source model

(ii) The solid flame model

In case of jet fire the object receives radiative heat transfer from the flame plume only. The radiative heat transfer from the buoyant gas plume is usually far less than 20 kW/m^2 which is the maximum emissive power of optical thick fire gases at a maximum temperature of 500°C). This radiative contribution from the buoyant gas plume can be neglected when considering the heat transfer onto a target some distance away from the fire.

Two different methods can be used when predicting the incident heat flux onto a target from flame plume, namely the 'point source model' and the 'solid flame model' where the former is far more simple and less accurate than the other especially at locations close to the fire.

The point source model

The 'point source model' is a method which simplifies the problem significantly by assuming that the flame plume is represented by a point source of thermal energy. Further, it assumes that a certain specified fraction of the released energy is released by radiation.

However, the accuracy of the results may be insufficient, especially in the near field of a large pool fire. The radiative heat flux (q_r'') to a target may be expressed in the following way:

$$q_r'' = Q_R / 4\pi x^2 \qquad \text{………….(ii)}$$

$$Q_R = f_R . m_f . \Delta Hc \qquad \text{………….(iii)}$$

Where,

$Q_R =$ energy released by radiation (kW)

X = distance from the flame centre (m)

f_R = fraction of the heat released as radiation(-)

$m_f =$ burning rate (kg/s)

ΔHc = heat of combustion of the fuel (kJ/kg)

The Point source model' has been used successfully for flames which have a large flame height to diameter ratio (i.e. jet fires and diffusive flare fires from comparatively small openings compared to the flame height) except very close to the fire. In the near field the point source model will overestimate the incident heat flux, which is a great disadvantage when predicting safe distances for process equipment and human beings. Further, this method is unable to include the effects of wind (e.g. flame tilt and flame drag) satisfactorily.

Some common type of gases have radiative fraction as given in below table:-

Type of Gas	Chemical formula	Radiative fraction f_R (-)
Hydrogen	H_2	0.2
Methane (C_1)	CH_4	0.2
Ethylene (C_2)	C_2H_2	0.25
Propane (C_3)	C_3H_8	0.3
Butane (C_4)	C_4H_{10}	0.3
C_5 and higher		0.4

Table 2.1: The fraction of the total combustion energy resulting in thermal radiation

Assessment

Due to a fire exposure of a pressurized tank containing butane, the contents are vented into the atmosphere from the top of the tank. The gas is immediately ignited forming a turbulent gas jet. The heat flux onto the ground 10 meter from the tank shall be predicted when assuming the heat of combustion of the fuel is taken as 4500 kJ/kg, burning rate is 220 kg/s and fraction of the heat released as radiation 0.3 (from table 2.1)

Now, from eqn. (iii) & (iv) Energy released by radiation (kw) & The radiative heat flux

Q_R = 29700 kw and
$q_r'' = 236$ kw/m^2

The solid flame model

The solid flame model is the most usual method used and which yields the most accurate results (irrespective of fire scenario) both in the near and far field of any fire. This model considers the flame as a body which emits thermal radiation. The shape or geometry of this body may be idealized as a cylinder or a cone for all fires except fireball scenario which maybe idealized as a sphere.

The incident radiation heat flux will be according to equation:

$q''_r = E_p.F.\tau$ ……………….(iv)

where

E_p = Average surface emissive power of the flame (kw/m^2)
F = view factor between the flame and the target(-) τ = atmospheric transmissivity = $0.79[100/r]^{0.0625}$ $.[30.5/x]^{0.0625}$
r = Relative humidity of the atmosphere (mostly 50%) x = Distance from flame surface to exposed target

where

$E_p = \varepsilon.\sigma.T_f^4$ …………………...(v)

Where ε = emissivity of the flame
σ = Stefan Boltzmann's constant = 56.7×10^{-12} KW/m^2.K^4T_f = Flame temperature (K).

Some common types of gases have emissive power by assuming black body radiation as given in below table:-

Type of Hydrocarbon	Temperature (K)	Emissive Power (kw/m^2)
Methane	1289	157
Ethane	1590	362
Ethylene	1722	498
Propane	1561	336
Isobutane	1554	330
Normal Butane	1612	383
Propylene	1490	279
Isobutylene	1409	223

Table 2.2: Effective flame temperature and emissive powers

Assessment

Due to a fire exposure of a pressurized tank containing butane, the contents are vented into the atmosphere from the top of the tank. The gas is immediately ignited forming a turbulent gas jet. The incident radiation heat flux onto the ground 10 meter from the tank shall be predicted, the value of atmospheric transmissivity $\tau = 0.79[100/r]^{0.0625}$ $.[30.5/x]^{0.0625}$ where r = 0.5 and x=10 m

τ =1.49 and the value of E_p = Average surface emissive power of the flame = 383 kw/m^2 from table 2.2 maximum view is taken as 0.1

Thus, the incident radiation heat flux will be according to equation (iv)

$q''_r = 57$ kw/m^2

Heat Transfer Assessment of Diffusive Fire

A diffusive gas fire may arise from a massive release of a flammable gas or vapour in an enclosed space which escapes diffusively out from one or several openings of the enclosed space. The concentration of fuel gas is too high in the enclosure to cause a fire within the enclosed space. The gas is burning outside the enclosure from its openings where the fuel comes into contact with sufficient air. Buoyancy controlled diffusion flames will emerge from the openings of the enclosure.

The preceding leakage scenario may in addition to a massive gas release also be a continuous or more or less massive instantaneous release of an unstabilized oil which flashes off considerable amounts of gas as well as light oil fractions due to a high temperature of the oil.

Since a diffusive gas fire is a buoyancy controlled fire, the calculation methods proposed in jet fire are similar. When calculating radiative heat transfer intensities incident on target some distance away from the fire, it is most convenient to use the solid flame model.

Liquid Fires

Various types of liquid fires may occur when a liquid fuel is released depending on the environment(s) of the release and the release mode. It is convenient to classify liquid fires into the following types:

- Pool fire in the open air
- Pool fire on the sea surface
- Pool fire in an enclosed area
- Fireball

A 'Pool fire in the open air' may take place when there is an ignition of a liquid spill which is released on a horizontal solid surface in the open air (e.g. on the ground) If this spill takes place on the sea surface, a 'Pool fire on the sea surface' may result. Likewise, if the liquid fuel is released within an enclosed space, a 'Pool fire in an enclosed area', which may suffer from more or less air deficiency, will result.

A 'Fireball' is a fire event which results from a 'BLEVE' (Boiling Liquid Expanding Vapour Explosion) in which an immediate ignition of the pressurized and liquefied fuel occurs. A 'Running liquid fire' is achieved when the liquid fuel is released on a surface which is not horizontal (e.g. the mantel walls of a tank container). The fuel burns as it flows down the surface. If the liquid fuel is released under high pressure so that it is dispersed into droplets, a so-called 'Spray fire' may occur.

Owing to the fact that the types of fires mentioned above will exhibit widely different burning characteristics, it is necessary that they are treated separately. All these fires except for the latter two, will be treated in this chapter with respect to prediction methods for important fire characteristics. 'Running liquid fires' and' Spray fires', are not dealt with here due to the fact that there are very few prediction methods for these fires.

Heat transfer assessment of fire ball

The preceding event for a fireball may be a pool fire enveloping a pressurized storage tank containing liquefied gas or a jet fire impinging on the storage tank. After some time, the tank will rupture due to the intense heating. A BLEVE (Boiling Liquid Expanding Vapour Explosion) with overpressure at the source in the order of 0.05 bar will occur.

Another preceding accident causing this fire scenario is a major structural damage of the tank leading to a more or less full rupture of the tank. Volatile fuels are being transported in rapidly increasing volumes both by highway vehicles and trains which may be exposed to accidents (collision and derailment). A spark ignition may easily occur in such situations resulting in a BLEVE/fireball.

A fraction of the liquefied fuel subsequently released will evaporate immediately and take part in a more or less huge fireball which has the shape of a hemispherical burning cloud or ball of fire which emits heat radiation over a relatively short period of time. The strong buoyancy force of the hot combustion gases results in a highly turbulent cloud in which rapid air entrainment occurs. A hemispherical shape is maintained during most of the initial expansion until the fireball growth is exceeded by the buoyancy, and then the spherical shape develops. Once completely formed, the fireball will lift off entraining further air which results in a cooling of the fireball. Normally the complete process takes 5 - 30 sec. It is the high degree of turbulent mixing and rapid air entrainment which allow large quantities of fuel to be consumed in such a short period of time.

The major hazards from BLEVEs/fireballs are blast effects, projectiles and thermal radiation. Some BLEVE incidents have shown that close to the container the physical blast during the rupture is equivalent to a wind speed of about 100 km/h. Further, BLEVE incidents have caused projectiles to be thrown up to 600 m. Perhaps the most serious aspect of fireballs is their effect on people who may suffer severe burns some distance away from the fireball. Owing to the short duration of a fireball and the thermal inertia of buildings and process equipment, it is unlikely that such constructions will be damaged due to the thermal heat loads even by 100 ton fireballs.

The incident radiation to a target at a distance ‘x’ from the fireball centre is given by :

$$q_r'' = \tau.F.Ep$$

Where τ is the atmospheric transmissivity, where x is equal to the radial distance x’, and F is the view factor of the target with respect to the fireball.

Other Fire Hazards

BLEVE

BLEVEs (Boiling Liquid Expanding vapor explosions) and explosions involving liquefied gas cylinders are dramatic incidents. There is always potential for loss of life and severe property damage during such incidents.

BLEVEs occur when a contained liquid is well above its boiling point at normal atmospheric pressure, causing the container to break into two or more pieces. This phenomenon can happen to any contained liquid that meets the boiling point/pressure situation.

BLEVE is an explosion involving both rapid vaporization of liquid and the rapid expansion of vapor in the vessel. It is initiated by fire and causes the vessel failure. In a typical BLEVE, vessel failure results from overheating upon exposure to fire. BLEVE is also a cause of concern because of large potential for damage.

Many other confined products can explode when pressure builds. For example, a 55 gallon drum, half filled with water and with bungs tightly in place, can be dangerous in a fire. The fire can boil the water increasing the pressure. Increased pressure forces the drum to expand and eventually explode. The drum can be propelled hundreds of feet. This problem magnifies if the drum contains a flammable, corrosive, or other dangerous product.

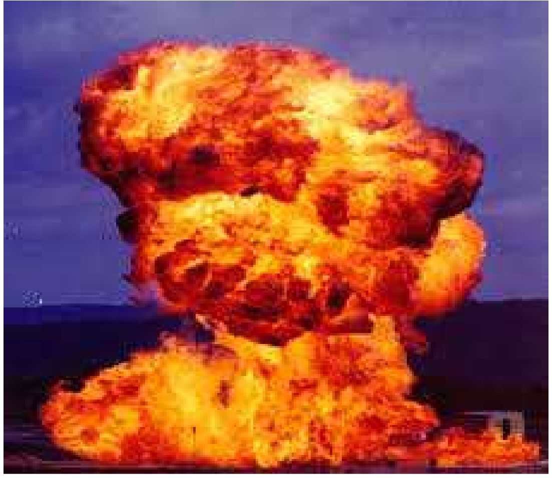

Figure2: Effect of BLEVE

Conclusion

Since the beginning of industrial revolution, accidents caused in storage of hydrocarbons are increased significantly. In order to reduce the accidents and unintentional events, this paper considers various models to control the miss happening in storage of oil and gases in a petroleum refinery.

According to this paper for hydrocarbon liquid and gas are taken into account and it can also suggest the design and construction criteria for the safe storage. It deals over various problem and difficulties of oil and gas industries like Flash Fire , Jet Fire, Diffusive Gas Fire, pool Fire, BLEVE, Fire Ball Hazard, LPG Hazard and many more.

When proper attention paid towards the safety of storage tank, hazardous area classification, separation distances, secondary containment, application of water and foam against fire in action, there will be sound result in terms of safety of health, environment and property.

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